

# Formation of Large-Scale Structure and the Hot IGM

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## Outline

- ❖ The Computation of the Evolution of the Universe is an Initial Value Problem Amenable to
- ❖ Numerical Simulations
- ❖ Formation of LSS and Evolution of Cosmic Gas
- ❖ Conclusions

## The Universe is an Initial Value Problem.....

- ❖ *Globally*, the universe evolves according to the Friedman equation

$$H^2 = \left( \frac{da}{dt} \right)^2 = \frac{8\pi G}{3} \Omega_m r_{crit} \pm \frac{k}{a^2} + \frac{\Lambda}{3}$$

Diagram illustrating the components of the Friedman equation:

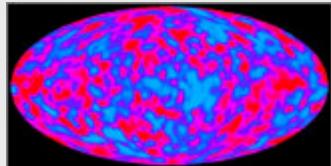
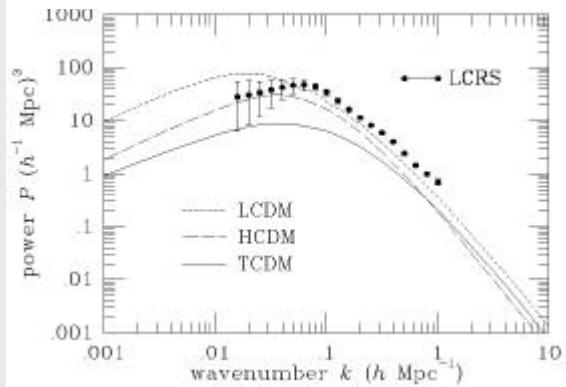
- Hubble constant:  $\frac{da}{dt}$
- scale factor  $a(t)$
- density parameter:  $\Omega_m r_{crit}$
- cosmological constant:  $\frac{\Lambda}{3}$

## The Universe is an Initial Value Problem.....

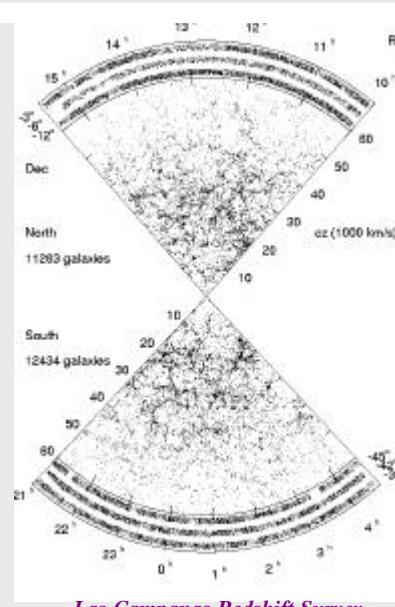
- ❖ *Locally*, it obeys Newtonian equations of gravitational dynamics for:
  - collisionless dark matter (CDM, HDM)
  - primordial gas (baryons)
- ❖ Atomic, molecular, and radiative processes important for the formation of stars, galaxies and galaxy clusters from gas

# Initial Conditions

- ❖ Gaussian random field  $\delta\rho(\mathbf{x})$
- ❖ Linear power spectrum  $P(k)$

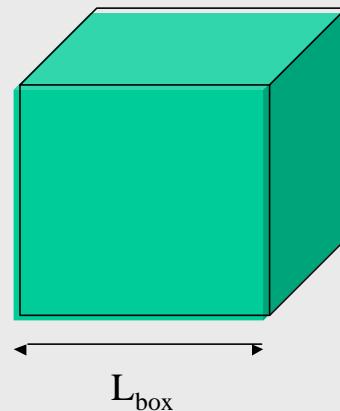


*COBE  
+BOOMERANG  
+MAXIMA  
+ ...*

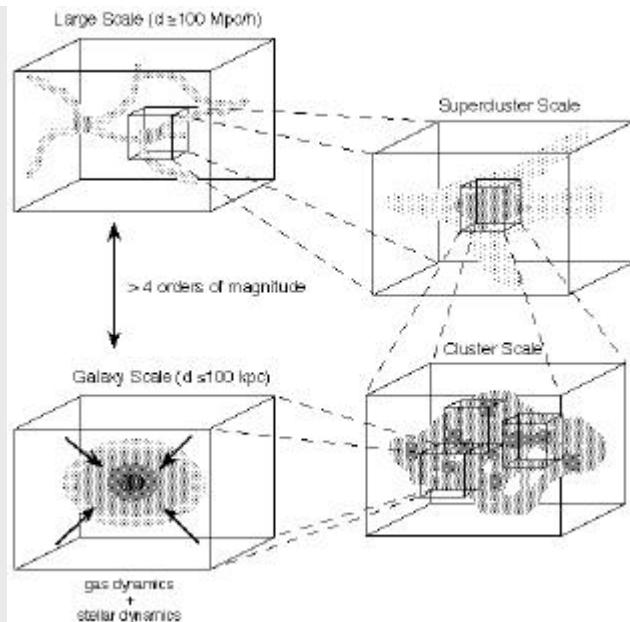


# Computing the Universe Using Numerical Simulations

- ❖ Transformation to  
*comoving coordinates*  
 $x=r/a(t)$
- ❖ comoving cube,  
periodic boundary  
conditions
- ❖  $L_{\text{box}} \gg \lambda_{\text{nl}}$



# Multiscale Challenge

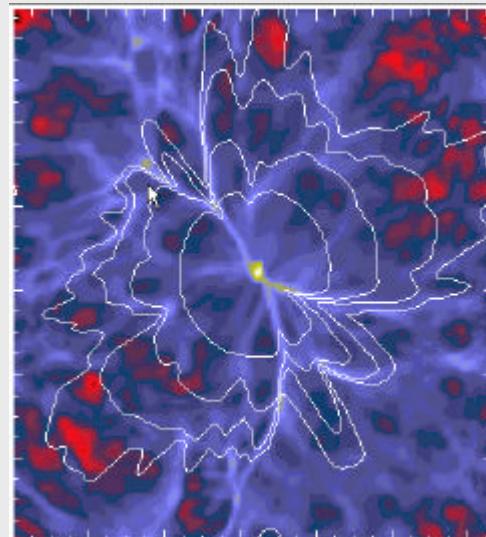


*dynamic range requirement:*  
 $> 10^4$  spatial  
 $> 10^9$  mass

[http://zeus.ncsa.uiuc.edu:8080/GC3\\_Overview.html](http://zeus.ncsa.uiuc.edu:8080/GC3_Overview.html)

# Multiphysics Challenge

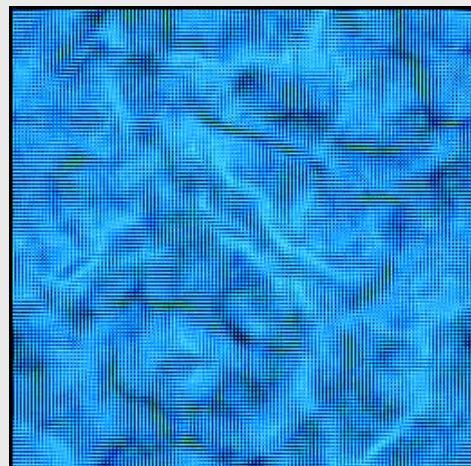
- ❖ Important physical processes
  - ✓ gravity
  - ✓ cosmic expansion
  - ✓ collisionless dark matter
  - ✓ gas dynamics
  - ✓ atomic/molecular physics
  - ✓ radiation transfer
  - ✓ photoionization
  - magnetic fields



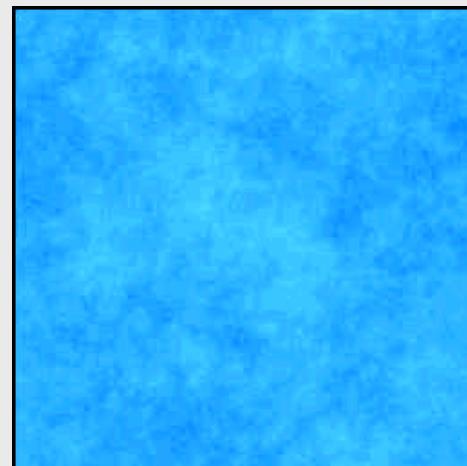
*quasar photoionization region  
(T. Abel & M. Norman, NCSA)*

# Evolution of Intergalactic Gas

dark matter density  
( $40 < z < 0$ )



baryonic gas density  
( $40 < z < 0$ )

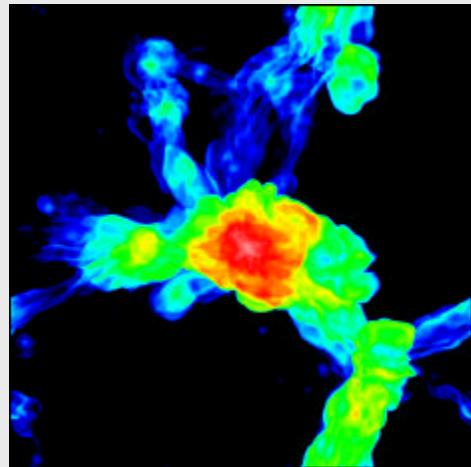


64Mpc

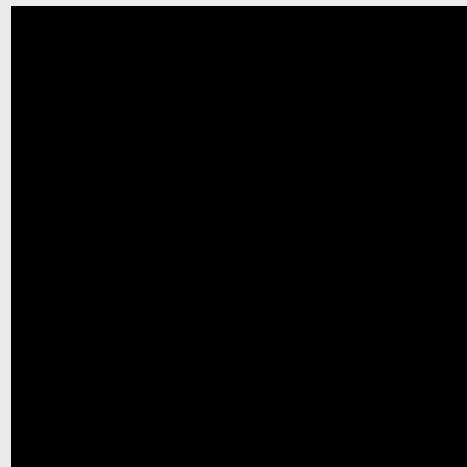
Animation (double click)

*Cen, Bode, Ostriker & Xu (1996, <http://astro.princeton.edu/~bode/TVD/index.htm>)*

## Shocking of IGM

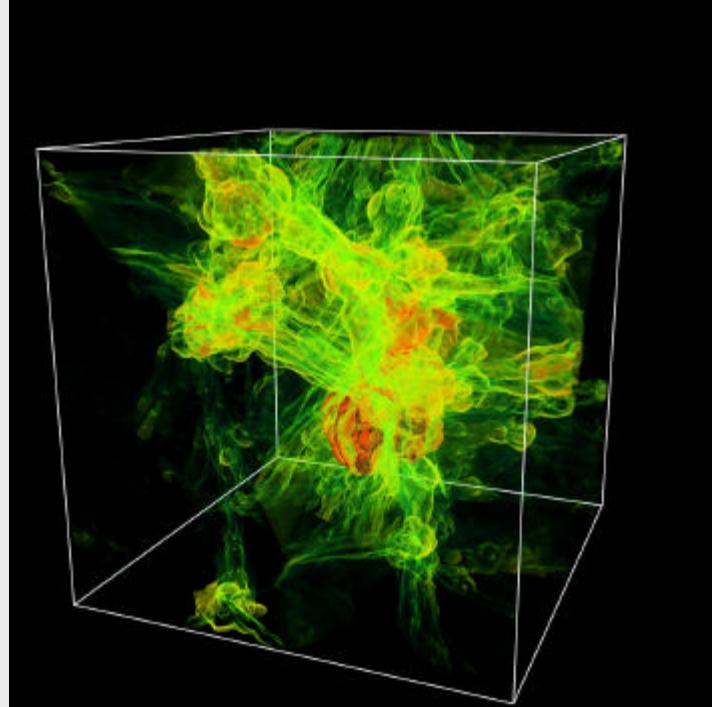


$\log(T)$  at  $z=0$

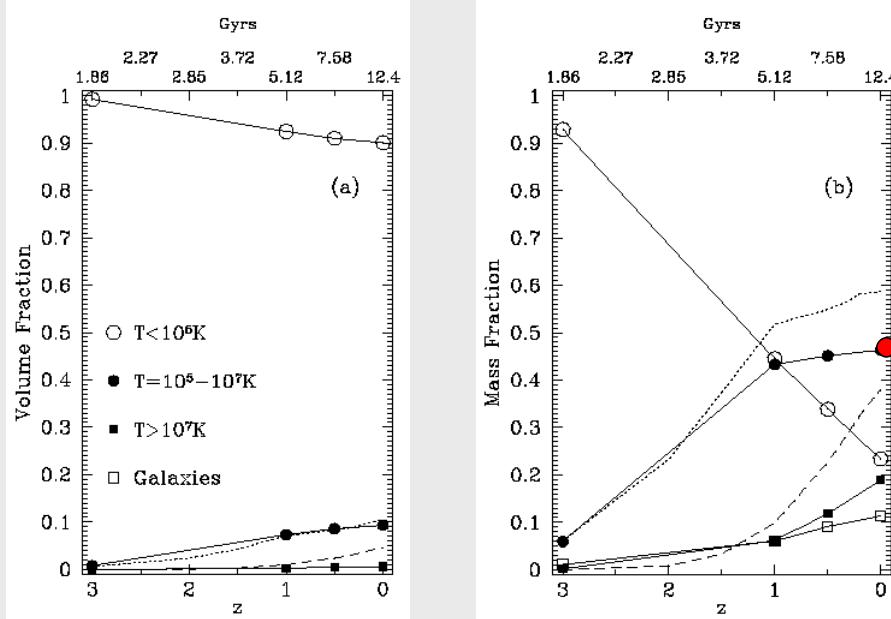


Animation (double click)

## Shocking of IGM

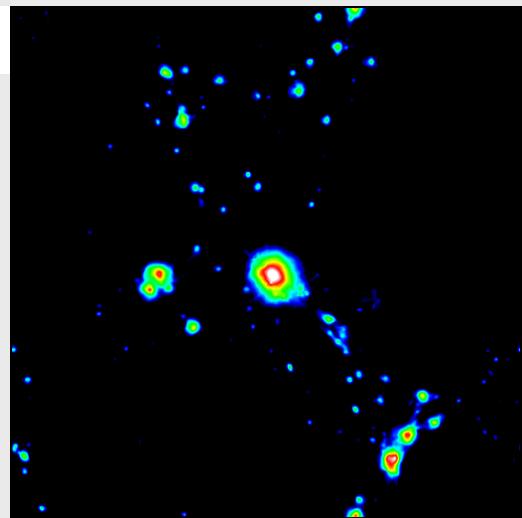


# Baryon Budget



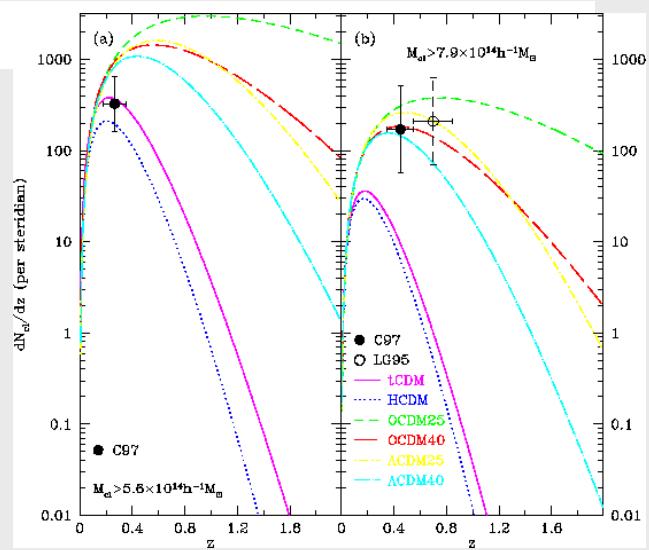
Cen & Ostriker (1999, ApJ, 514, 1)

## The T>10<sup>7</sup>K Gas: X-ray Clusters



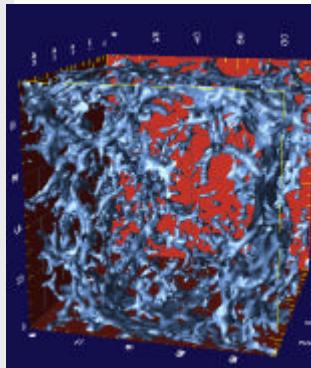
*Cen, Bode, Ostriker & Xu (1996)*

# Evolution of X-ray Clusters

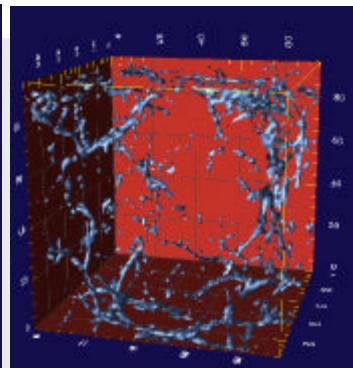


Cen (1998, ApJ,  
509, 16)

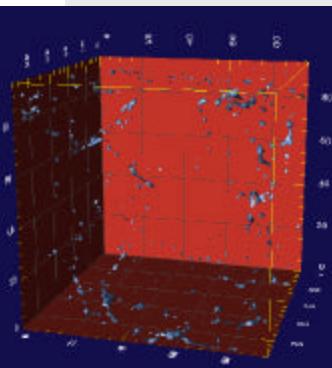
## The T<10<sup>5</sup>K Gas: The Lyman Alpha Forest



$\rho=3$

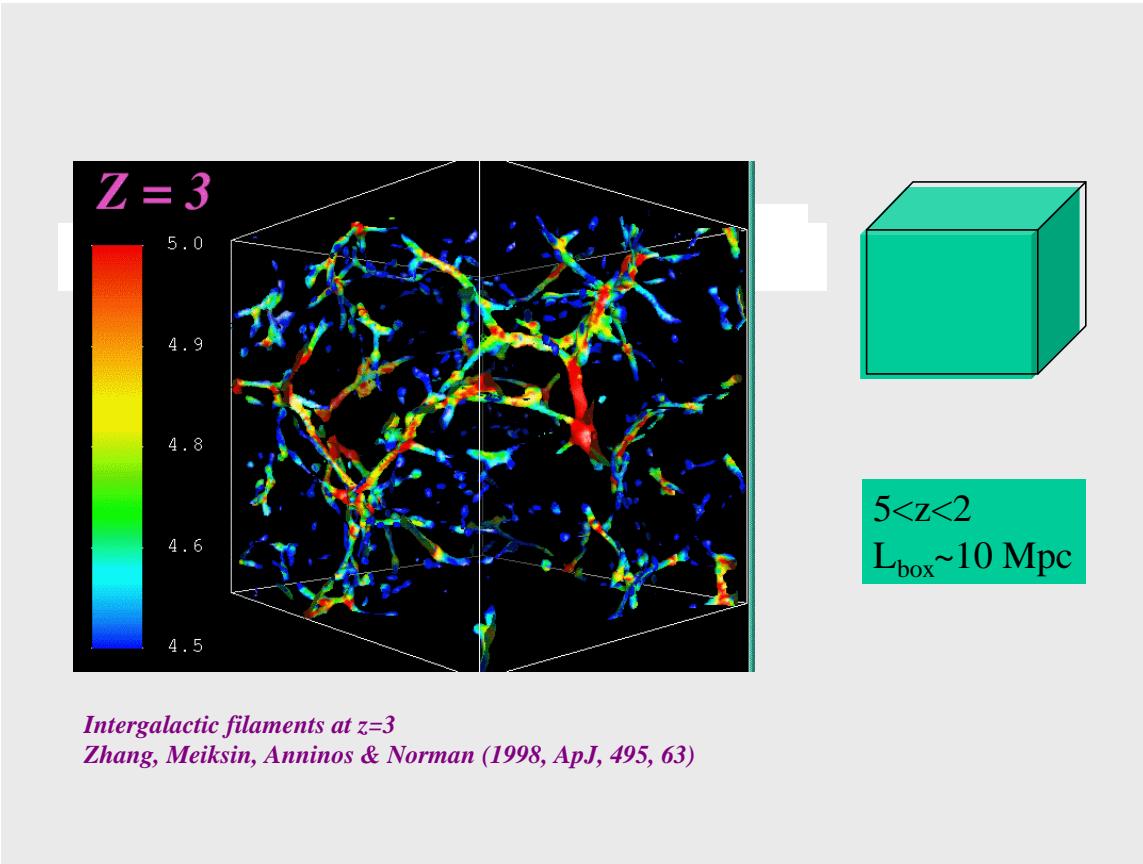


$\rho=10$

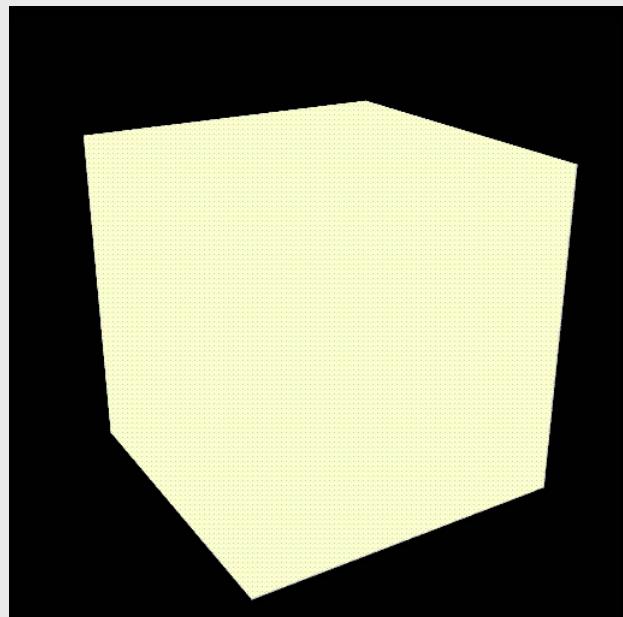


$\rho=30$

*Intergalactic filaments at  $z=3$ ,  $L_{box}=10\text{Mpc}$   
Cen and Simcoe (1997, ApJ, 483, 8)*



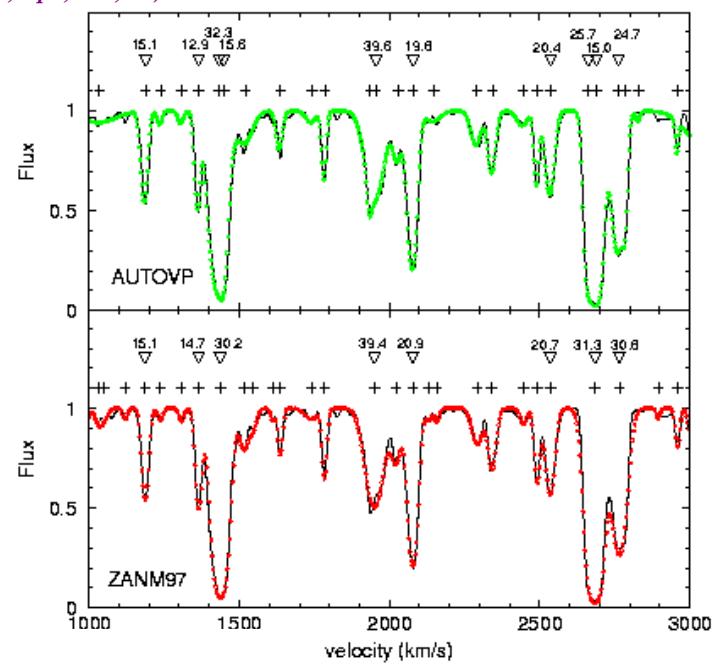
## Evolution of neutral gas



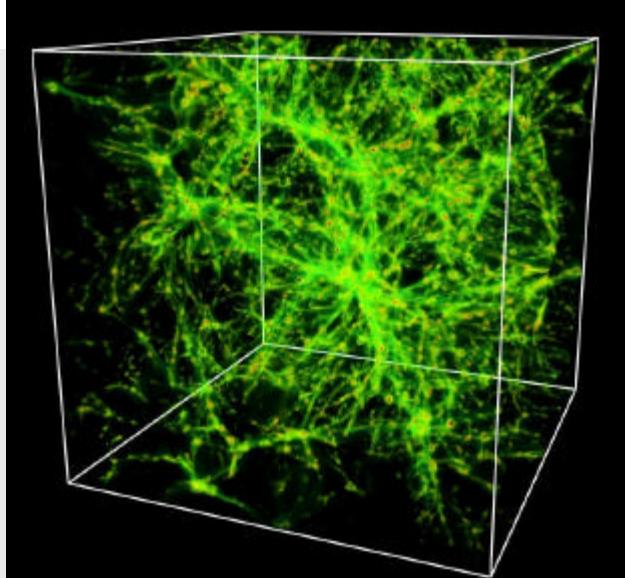
*Cen et. al (2000,  
in preparation)*

# Synthetic Ly $\alpha$ absorption spectrum

Bryan et al. (1999, ApJ, 517, 13)



## T=10<sup>5</sup>-10<sup>7</sup>K Gas: Warm-Hot Intergalactic Medium (WHIM)

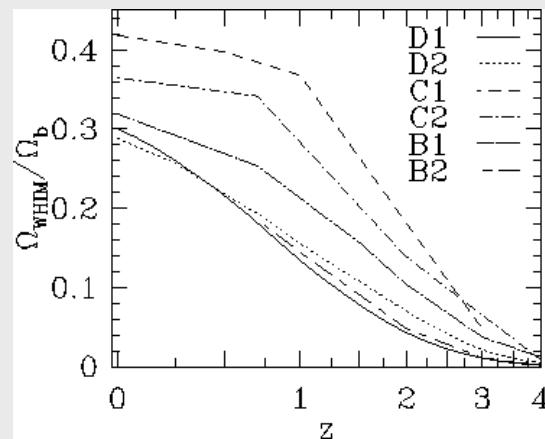


$L_{\text{box}} = 100 \text{Mpc}/h$

*Hot and warm gas in the  
Intergalactic medium  
Cen & Ostriker (1999,  
ApJ, 514, 1)*

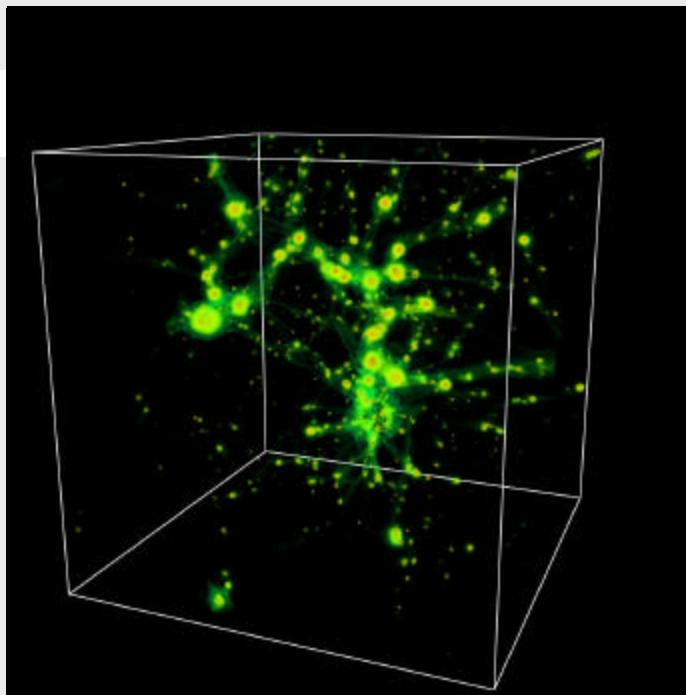
## WHIM results are robust

Dave et al. (2000, astro-ph/0007217)



Physical reason:  
 $\langle T \rangle \sim (H L_{nl})^2$

## Evolution of WHIM



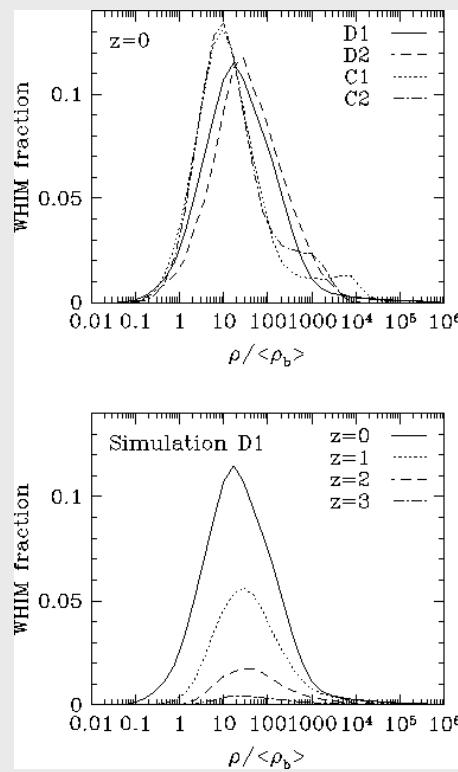
$z=6 \rightarrow 0$

$L_{\text{box}} = 25 \text{Mpc}/h$

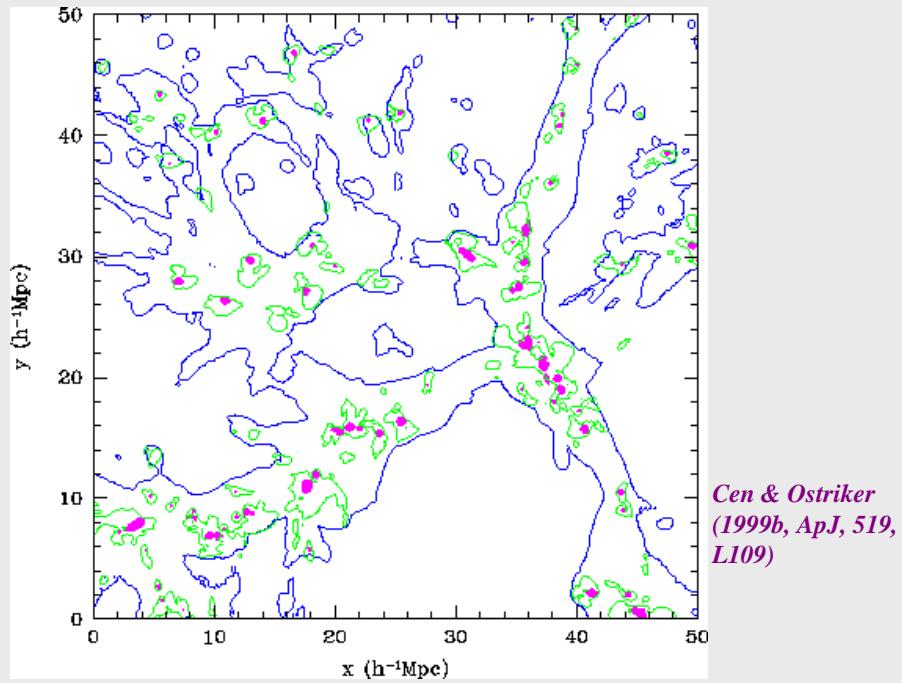
*Cen & Ostriker (2000,  
in preparation)*

# Density of the WHIM gas

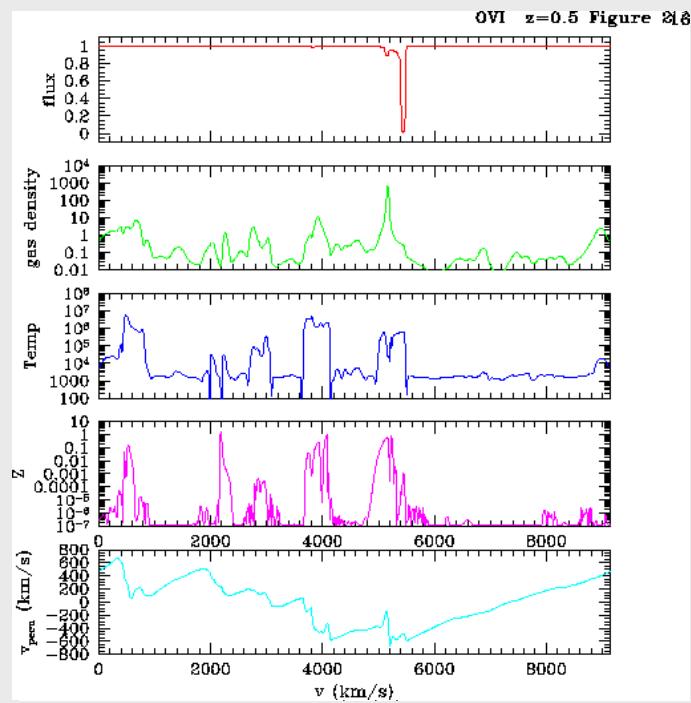
*Dave et al. (2000, astro-ph/0007217)*



# Galaxies, WHIM and Metals



# Observing the WHIM I: Absorption



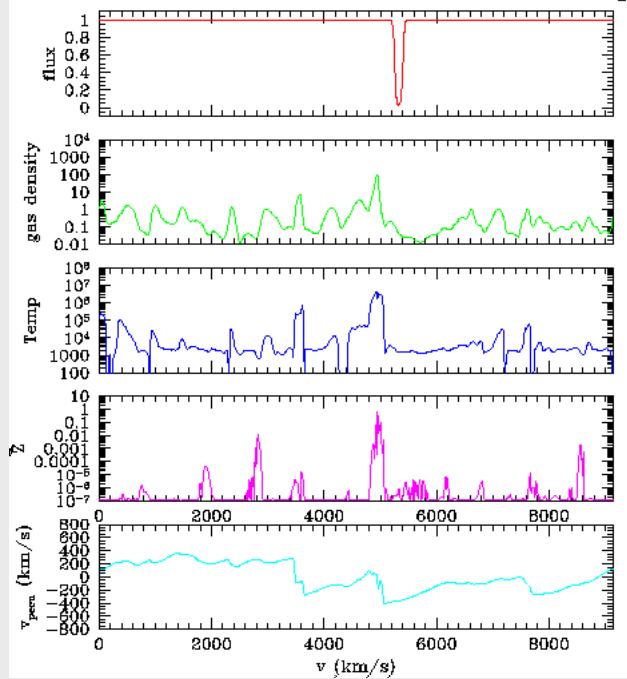
OVI line

$d\eta/dz \sim 1$

Cen et al. (2000,  
in preparation)

# OVII line

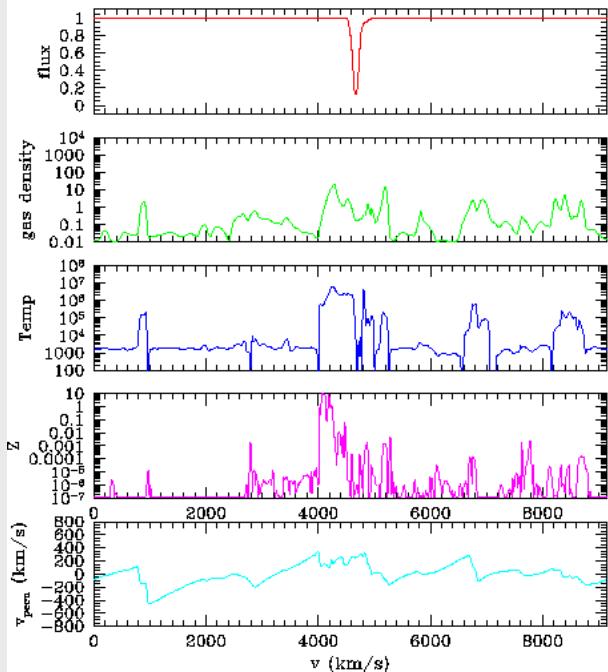
OVII z=0.5 Figure 24



dn/dz~1

## OVIII line

OVIII z=0.5 Figure 19



$dn/dz \sim 1$

## Observing the WHIM II: Emission

- ❖ Individual emission
- ❖ X-ray background

## Conclusions

- ❖ The Warm-Hot Intergalactic Medium is 40% of the total baryon today, an inevitable consequence of formation of large-scale structure
- ❖ It may be best detected in absorption lines; Chandra may be able to see them; Con-X? Yes!